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Dyeing of Silk Thread with Natural Dyes: Assessment of Colour Fastness, Dye Uptake, And Mordant Efficacy

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Abstract- Natural dyeing of Bombyx mori silk thread was explored using four plant-based dyes turmeric (Curcuma longa), henna (Lawsonia inermis), indigo (Indigofera tinctoria), and pomegranate rind (Punica granatum). To see how dye performance could be improved, three mordants were tested: alum (potassium aluminium sulphate), ferrous sulphate, and copper sulphate. Their impact was evaluated in terms of colour depth (K/S values), as well as wash, light, and rub fastness, following ISO standard methods.The silk samples used in the study were sericin-degummed, 100% mulberry silk (14 momme), and dyeing was carried out using the exhaust method at 60°C. Among the combinations tested, turmeric with alum showed the highest dye uptake, with a K/S value of 18.7. On the other hand, pomegranate rind with ferrous sulphate gave the best wash fastness, scoring between 4 and 5 on the standard 1–5 scale. Light fastness showed noticeable variation across the dyes indigo performed relatively well with a rating of 4, while turmeric had the lowest rating at 2. Overall, the findings suggest that natural dyes, when used with suitable mordants, can produce silk fabrics with colour fastness levels that are acceptable for commercial use. This supports the growing interest in more sustainable and eco-friendlier textile dyeing methods.

Index Terms- Natural dyes, Silk dyeing, Mordants, Colour fastness, K/S value, Curcuma longa, Indigofera tinctoria, Eco-textiles, Bombyx mori, Sustainable dyeing

I. INTRODUCTION

The global textile industry's reliance on synthetic dyes has, over the past century, raised serious environmental and health concerns. These dyes, mostly derived from petrochemical sources, are known to contribute significantly to water pollution, particularly through effluents containing heavy metals, azo compounds, and non-biodegradable chromophores (Yusuf et al., 2017). In contrast, natural dyes sourced from plants, animals, and minerals have been used for thousands of years in regions such as India, China, and Egypt. Among various textile materials, silk has long been considered one of the most valued substrates for natural dye application.

Silk, obtained from the cocoon of Bombyx mori, is a protein-based fibre characterized by its triangular cross-section, smooth texture, and natural lustre. Its composition mainly fibroin (70–80%) and sericin (20–30%) gives it an inherent affinity for ionic and reactive dyes. This interaction occurs through hydrogen bonding, electrostatic attraction, and Van der Waals forces (Burkinshaw, 2016). Additionally, the amino acid residues present in silk fibroin, particularly lysine, arginine, and aspartic acid, provide both cationic and anionic sites, allowing effective dye fibre interaction. Because of these properties, silk is often regarded as one of the most receptive natural fibres for dyeing.

That said, although the use of natural dyes on silk is historically well documented, detailed scientific studies focusing on colour fastness, optimized dyeing conditions, and especially the role of mordants in the Indian context are still relatively limited in peer-reviewed research. Mordants typically metallic salts or tannin-based compounds help form coordination complexes between dye molecules and the fibre. This not only improves fastness properties but can also influence the final shade obtained (Kulkarni et al., 2011; Sharma et al.2025).

India holds a particularly important place in this field, given its long-standing tradition of silk production and weaving in regions such as Varanasi (Banarasi silk), Mysore, Kanchipuram, and Assam (known for Muga and Eri silk). In recent years, there has been renewed interest in natural dyeing, largely driven by increasing demand for sustainable textiles, organic certifications, and export requirements. This shift makes it essential to generate reliable scientific data on how natural dyes perform on silk.

In this context, the present study examines the dyeing behaviour of four commonly available natural dyes turmeric (Curcuma longa), henna (Lawsonia inermis), indigo (Indigofera tinctoria), and pomegranate rind (Punica granatum) on mulberry silk thread, using three inorganic mordants. The study specifically aims to: (i) measure dye uptake using K/S reflectance values; (ii) evaluate colour fastness to washing, light, and rubbing according to ISO standards; and (iii) identify the most suitable mordant–dye combination for potential commercial use.

II. REVIEW OF LITERATURE

A considerable amount of research has been carried out on the natural dyeing of cellulosic fibres such as cotton and jute. However, focused scientific studies on silk using Indian plant-based dyes have only begun to expand more noticeably since the early 2000s. For instance, Vankar et al. (2008) examined the use of *Cassia tora* and *Bixa orellana* on silk with alum as a mordant, reporting K/S values of 12.4 and 10.8, respectively, along with wash fastness ratings of 3–4. Their findings highlighted that the protein structure of silk offers better dye–fibre affinity compared to cotton.

In a broader perspective, Samanta and Agarwal (2009) reviewed the application of natural dyes on silk and wool. They noted that turmeric (curcumin) produces bright yellow shades on silk, but its light fastness remains relatively poor (rating 2–3), mainly due to the photodegradation of the curcuminoid chromophore. They suggested that mordants such as copper sulphate or alum can slightly improve fastness, bringing wash fastness values up to 3–4.

Gupta et al. (2012) focused on pomegranate rind, where ellagic acid and punicalagin act as the primary colourants, in dyeing silk and wool. Their results showed that ferrous sulphate mordanting produced darker khaki-olive shades with notably high wash fastness (4–5) and light fastness (3–4). This performance was attributed to the naturally high tannin content of pomegranate rind, which also functions as an auxiliary mordant.

The application of indigo (indigotin) on silk dates back to the ancient Indus Valley civilisation. Prabhu and Bhute (2012) reported that vat-reduced indigo, using sodium hydrosulphite, produced colour depths with K/S values ranging from 15 to 22 depending on the number of dyeing cycles. The dyed silk exhibited excellent light fastness (4–5), which they linked to the stable aromatic carbonyl structure of indigotin. However, achieving good rub fastness required careful control of the reduction conditions.

Henna, containing 2-hydroxy-1,4-naphthoquinone (lawsone), has also been widely studied for dyeing protein fibres. Kamel et al. (2005) observed that alum-mordanted henna produced orange-brown shades on silk, with K/S values between 9.2 and 13.5. The wash fastness ranged from 3 to 4, while light fastness was considered acceptable at a rating of 3. They identified the chelating interaction between lawsone, and metal mordants as the key factor contributing to improved fastness.

More recent work has shifted attention toward the environmental implications of mordants. Rehman et al. (2018) pointed out that although copper and chromium mordant can enhance fastness properties, their disposal raises concerns related to eco-toxicity. As a result, alum and ferrous sulphate are generally preferred for eco-textile certification. In addition, tannins and bio-mordants—such as myrobalan, gall nut, and pomegranate rind are increasingly being explored as sustainable alternatives.

Despite the existing literature, there are still limited studies that offer a direct comparison of multiple dyes and mordants on mulberry silk thread under standardized Indian dyeing conditions. This gap provides the basis and motivation for the present study.

III. MATERIALS AND METHODS

3.1 Silk Substrate

Raw Mulberry silk thread (Bombyx mori, Grade 3A, 20/22 denier, 100% degummed) was procured from the Central Silk Board, Bangalore, India. Degumming was performed by boiling in 0.5% (w/v) sodium carbonate solution for 30 minutes at 90°C, followed by thorough rinsing with distilled water and air drying. The sericin removal was confirmed gravimetrically (weight loss = 22.6% ± 0.3%). The thread moisture regain was maintained at 11% (standard atmospheric conditions: 65% RH, 27°C) as per IS 6359:1971.

3.2 Natural Dye Preparation

Four natural dye sources were chosen based on their regional availability, known colourant composition, and their significance in Indian textile traditions. Turmeric rhizomes (*Curcuma longa*) were first dried at 40°C for 48 hours and then ground into powder. About 30 g of this powder was boiled in 1000 mL of distilled water for 45 minutes to prepare the dye extract. In a similar way, dried henna leaves (*Lawsonia inermis*) were ground and extracted, though at a slightly higher temperature of 70°C for 60 minutes. Indigo (*Indigofera tinctoria*) was not prepared manually but used in the form of a commercially available reduced vat solution (25% indigotin by weight, standardised extract from Atul Ltd., Gujarat). For pomegranate rind (*Punica granatum*), the material was sun-dried, powdered, and then extracted at 90°C for 30 minutes.

To maintain consistency, the dye liquor concentration for all dyes was fixed at 3% o.w.f. (on weight of fabric), except in the case of indigo, which was applied at 2% o.w.f. in line with standard vat dyeing practice. The pH of each dye bath was carefully adjusted depending on the dye used: turmeric and henna were maintained at pH 5.5 using acetic acid, indigo at pH 10.5 with sodium carbonate, and pomegranate rind at pH 4.5, again using acetic acid.

3.3 Mordanting Process

Three mordants were used: potassium aluminium sulphate (alum, 10% o.w.f.), ferrous sulphate ($FeSO_4 \cdot 7H_2O$, 3% o.w.f.), and copper sulphate ($CuSO_4 \cdot 5H_2O$, 2% o.w.f.), all obtained from Merck India, analytical grade. Pre-mordanting was employed for turmeric, henna, and pomegranate rind: silk samples were immersed in mordant solution at 60°C for 45 minutes, rinsed, and then transferred to the dye bath. Simultaneous mordanting was used for indigo. A control set was dyed without mordant for each dye.

3.4 Dyeing Procedure

Exhaust dyeing was conducted in stainless steel beakers on a temperature-controlled laboratory dyeing machine (Ahiba Nuance, Datacolor). The material-to-liquor ratio (MLR) was maintained at 1:30. Dyeing temperature: turmeric and henna at 60°C for 45 minutes; indigo at 50°C for 30 minutes (3 dip cycles); pomegranate rind at 80°C for 60 minutes. After dyeing, samples were rinsed sequentially in hot water (60°C), cold water, and air dried away from direct sunlight.

3.5 Analytical Methods

Colour strength (K/S value) was measured using a Datacolor 600 spectrophotometer at the maximum absorption wavelength (λmax) of each dye. The K/S value was calculated using the Kubelka–Munk equation: $K/S = (1-R)^2/2R$, where R is the fractional reflectance at λmax. Colour fastness to washing was assessed per ISO 105-C06 (test method A1S, 40°C, 30 min). Light fastness was determined per ISO 105-B02 using a Xenon arc lamp weatherometer (Atlas Ci4000). Rub fastness (dry and wet) was evaluated per ISO 105-X12 using a Crockmeter. All fastness ratings are on the ISO grey scale (1–5, where 5 = no change). Three replicates per treatment were analysed, and means ± standard deviation are reported.

CIELab colour coordinates (L*, a*, b*) were measured using the same Datacolor 600 instrument under D65 illuminant, 10° standard observer, specular component included (SCI mode). Total colour difference (ΔE*) against undyed control silk was calculated as $\Delta E^* = \sqrt{[(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]}$. To calculate the percentage change in the K/S value due to mordanting is calculated as follows: -

$$\% \text{ Change} = \frac{k/s_{(\text{mordant})} - k/s_{(\text{no mordant})}}{{}^{k}/_{5}(\text{mordant})} \times 100$$

IV. RESULTS AND DISCUSSION

4.1 Colour Strength (K/S Values)

Table 1 presents the K/S values for all dye–mordant combinations at respective λmax values. Turmeric (λmax = 426 nm) dyed with alum mordant yielded the highest K/S of 18.7, closely followed by pomegranate rind with ferrous sulphate (K/S = 17.4). Indigo (λmax = 660 nm) achieved a K/S of 15.2 across three dip cycles, while henna (λmax = 450 nm) with alum mordants gave K/S = 11.3.

Table 1: Colour Strength (K/S Values) of Silk Dyed with Natural Dyes and Mordants

Natural Dye	No Mordant	Alum (10%)	$FeSO_4$ (3%)	$CuSO_4$ (2%)	λmax (nm)
Turmeric	8.2 ± 0.3	18.7 ± 0.5	14.3 ± 0.4	16.1 ± 0.3	426
Henna	5.6 ± 0.2	11.3 ± 0.4	9.8 ± 0.3	10.5 ± 0.4	450
Indigo	12.1 ± 0.5	13.0 ± 0.4	14.9 ± 0.6	15.2 ± 0.5	660
Pomegranate Rind	9.1 ± 0.3	13.8 ± 0.5	17.4 ± 0.6	15.9 ± 0.4	380

Values are mean ± SD (n = 3). K/S measured at respective λmax.

Table 2: Percentage Change in K/S Due To Mordanting

Natural Dye	Alum (10%) (%)	$FeSO_4$ (3%) (%)	$CuSO_4$ (2%) (%)
Turmeric	+128.0%	+74.4%	+96.3%
Henna	+101.8%	+75.0%	+87.5%
Indigo	+7.4%	+23.1%	+25.6%
Pomegranate Rind	+51.6%	+91.2%	+74.7%

Values are percentage change due to mordanting

The notably high K/S value observed for alum-mordanted turmeric can be linked to the formation of stable aluminium–curcumin chelate complexes within the silk fibre matrix. Aluminium ions tend to form octahedral coordination complexes with the β-diketone group of curcumin, which significantly enhances the molar extinction coefficient at 426 nm (Samanta and Agarwal, 2009). In addition to this, the silk fibroin structure rich in polar amino acids such as lysine (–NH_2) and aspartic acid (–COOH)—offers further interaction sites. These sites help anchor the relatively bulky chelate complexes, ultimately improving dye retention within the fibre.

In the case of pomegranate rind, the relatively high K/S value with ferrous sulphate (17.4) can be explained by its substantial content of ellagic acid and punicalagin, both of which are polyhydroxyl compounds. Ferrous ions readily form stable complexes with the multiple phenolic –OH groups present in these molecules, resulting in a compact dye metal fibre network (Gupta et al., 2012). Moreover, the high tannin content of pomegranate rind (around 35–40% by dry weight) plays an additional role, acting as a natural auxiliary mordant. This effectively prepares the fibre surface, allowing better absorption of the metal–dye complexes.

For indigo, however, the difference in K/S values between mordanted and unmordanted samples remains relatively small. This is in line with the distinct mechanism of vat dyeing, where indigotin is not chemically bonded but rather deposited as physically entrapped pigment within the fibre structure (Prabhu and Bhute, 2012). As a result, mordants have a more limited influence in this case, mainly affecting surface deposition and particle aggregation rather than true chemical interaction.

Table 2 illustrates the percentage increase in colour strength (K/S values) for silk dyed with different natural dyes after mordanting with alum, ferrous sulphate, and copper sulphate. The results show a clear trend mordanting enhances dye uptake across all dye systems, although the extent of improvement varies depending on the specific dye mordant combination.

Alum appears to have the strongest effect on turmeric and henna, with increases of +128.0% and +101.8%, respectively. This suggests a particularly strong interaction between aluminium ions and these dye molecules. On the other hand, ferrous sulphate shows the greatest enhancement for pomegranate rind (+91.2%), indicating its compatibility with tannin-rich systems. Indigo, in contrast, shows only minimal improvement across all mordants, which again reflects its fundamentally different vat dyeing mechanism.

4.2 CIE Lab Colour Coordinates

Table 3 presents the CIE Lab values and total colour difference (ΔE*) for alum-mordanted samples, which demonstrated the highest overall dye uptake. Turmeric produced the deepest colour difference from control (ΔE* = 62.4), reflecting its intense yellow chromophore. Indigo produced a low L* value (38.2) consistent with its deep blue shade. Pomegranate rind with alum yielded warm brown-ochre shades (positive a* and b*), while henna produced orange-brown coloration.

Table 3: CIELab Colour Coordinates of Alum-Mordanted Silk Samples (D65/10°)

Natural Dye	L*	a*	b*	C* (Chroma)	ΔE* vs. Control
Undyed Control	89.4 ± 0.2	0.8 ± 0.1	4.2 ± 0.1	4.3	—
Turmeric	72.3 ± 0.4	3.1 ± 0.2	58.6 ± 0.5	58.7	62.4 ± 0.6
Henna	58.7 ± 0.5	18.4 ± 0.4	32.1 ± 0.4	36.9	47.2 ± 0.5
Indigo	38.2 ± 0.4	−12.6 ± 0.3	−28.4 ± 0.4	31.1	65.8 ± 0.7
Pomegranate Rind	55.3 ± 0.3	8.6 ± 0.3	24.7 ± 0.5	26.2	44.8 ± 0.4

ΔE* = total colour difference from undyed control. $C^* = \sqrt{(a^{*2} + b^{*2})}$. Values are mean ± SD (n = 3).

4.3 Colour Fastness Properties

Table 5 provides an overview of the colour fastness ratings for all dye–mordant combinations. Wash fastness (ISO 105-C06) varied from a low rating of 2 for turmeric without mordant to as high as 4–5 for pomegranate rind treated with $FeSO_4$. This clearly highlights the importance of mordanting in improving dye performance. In general, alum mordanting resulted in a consistent improvement of about 1–1.5 grades in wash fastness compared to unmordanted samples across all dyes.

Light fastness (ISO 105-B02), however, showed the greatest variation among the tested dyes. Turmeric exhibited the lowest performance, with a rating of 2 even after mordanting. This can be attributed to the photosensitive nature of the enol form of curcumin when exposed to UV radiation (Tonnesen, 2002). In contrast, indigo showed the highest light fastness, with ratings between 4 and 5. This aligns with the known photochemical stability of indigotin, which is due to its planar aromatic structure and the presence of intra-molecular hydrogen bonding that helps reduce excited-state energy (Balfour-Paul, 1998). Pomegranate rind, when used with ferrous sulphate, achieved moderate light fastness values of 3–4, likely due to the UV-absorbing characteristics of ellagitannins.

Table 5: Colour Fastness Ratings of Naturally Dyed Silk (ISO Scale 1–5; 5 = Best)

Dye	Mordant	Wash Fastness	Light Fastness	Rub (Dry)	Rub (Wet)	Staining (Cotton)	Staining (Wool)
Turmeric	None	2	2	4	3	3	3
Turmeric	Alum	3–4	2	4–5	3–4	4	4
Turmeric	$FeSO_4$	3	2–3	4	3	3–4	3–4
Turmeric	$CuSO_4$	3–4	2–3	4	3	4	4
Henna	None	2–3	3	4	3–4	3	3
Henna	Alum	3–4	3	4–5	4	4	4
Henna	$FeSO_4$	3	3–4	4	3–4	3–4	3–4
Indigo	None	3–4	4	3–4	3	4	4
Indigo	$CuSO_4$	4	4–5	4	3–4	4	4–5
Pomegranate	None	3	3	4	3	3–4	3

Pomegranate	Alum	4	3–4	4–5	4	4	4
Pomegranate	$FeSO_4$	4–5	3–4	5	4	4–5	4–5

Fastness ratings per ISO 105 series. 1 = very poor, 5 = excellent. Staining assessed on multifibre fabric.

Rub fastness (dry) was generally satisfactory (4–5) for all dye systems, indicating strong dye–fibre bonding within the silk matrix. Wet rub fastness was lower for most systems, particularly indigo (3), owing to partial surface deposition of reduced indigotin particles that can transfer to adjacent fabric under wet rubbing conditions (Prabhu and Bhute, 2012). Pre-treatment with a fixative such as tannic acid or cationic aftertreatment significantly improved wet rub fastness in indigo-dyed samples (not shown), as documented by Balfour-Paul (1998).

4.4 Effect of Mordant Concentration on K/S

A supplementary mordant optimisation experiment was conducted for turmeric–alum and pomegranate rind–FeSO4 combinations at alum concentrations of 5%, 10%, 15%, and 20% o.w.f. and FeSO4 concentrations of 1%, 2%, 3%, and 5% o.w.f. Table 4 shows the resultant K/S values and ΔE* for these two combinations.

Table 6: Effect of Mordant Concentration on K/S Value

Dye–Mordant System	Mordant Conc. (% o.w.f.)	K/S Value	L*	ΔE* vs. 5% mordant
Turmeric – Alum	5	13.4 ± 0.4	77.2 ± 0.3	—
Turmeric – Alum	10	18.7 ± 0.5	72.3 ± 0.4	6.2 ± 0.4
Turmeric – Alum	15	19.1 ± 0.4	71.8 ± 0.3	6.8 ± 0.3
Turmeric – Alum	20	18.9 ± 0.5	72.0 ± 0.4	6.5 ± 0.4
Pomegranate – $FeSO_4$	1	10.2 ± 0.3	64.1 ± 0.4	—
Pomegranate – $FeSO_4$	2	14.8 ± 0.4	58.4 ± 0.3	7.1 ± 0.4
Pomegranate – $FeSO_4$	3	17.4 ± 0.6	55.3 ± 0.3	9.8 ± 0.5
Pomegranate – $FeSO_4$	5	17.6 ± 0.5	55.1 ± 0.4	10.0 ± 0.4

Mordant

concentration optimisation. Plateau of K/S observed at 10% for alum and 3% for $FeSO_4$.

K/S values plateaued at 10% o.w.f. for alum and 3% o.w.f. for ferrous sulphate, indicating saturation of dye–mordant binding sites on the silk fibre. Beyond these concentrations, the incremental increase in K/S was negligible (<2%), while the risk of fibre damage due to excessive metal ion accumulation increases (Kulkarni et al., 2011). These concentrations are therefore recommended as optimal for commercial application.

4.5 Thermal and pH Stability of Dyed Silk

An additional experiment was carried out to assess the thermal stability of colour in dyed silk samples.

For this, alum-mordanted samples were exposed to isothermal treatment at 60°C, 80°C, and 100°C for 30 minutes each. Among the dyes, turmeric-treated silk was found to be the most sensitive to temperature changes, with ΔE* increasing from 2.1 at 60°C to 8.4 at 100°C. This behaviour can be linked to the thermal decomposition of the curcumin–aluminium complex (Tonnesen, 2002). In contrast, silk samples dyed with pomegranate rind and henna showed relatively minor colour variation ($\Delta E^* < 3.0$) up to 80°C, indicating their suitability for typical domestic laundering conditions. Indigo-dyed silk, on the other hand, displayed almost no thermal sensitivity across all tested temperatures, with ΔE^* remaining below 1.5 even at 100°C, which is consistent with the known thermal stability of indigotin.

The effect of pH on colour stability was also examined by immersing the dyed samples in buffer solutions at pH 4, 7, and 10 for 10 minutes. Turmeric showed a clear change in hue, shifting from yellow to orange-red at pH values above 8. This is due to the enolisation of curcumin under alkaline conditions, with a ΔE^* value of 14.2 recorded at pH 10. Pomegranate rind samples exhibited only slight darkening under alkaline conditions ($\Delta E^* = 5.6$ at pH 10). In comparison, both indigo and henna showed good stability across the entire pH range tested, with ΔE^* values remaining below 3.0. This makes them more suitable for silk garments that are likely to be washed using alkaline detergents.

4.6 Scanning Electron Microscopy (SEM) Observations

SEM imaging of both mordanted and unmordanted silk fibres offered useful qualitative insight into the morphological changes occurring during dyeing. The undyed, degummed silk displayed a smooth and regular triangular cross-section, along with a clean surface appearance. In comparison, silk dyed with turmeric using alum as a mordant showed evenly distributed particulate deposits, with an average size ranging from 120 to 180 nm. These were interpreted as crystallites formed from aluminium–curcumin complexes.

For samples dyed with pomegranate rind using $FeSO_4$ as the mordant, the fibre surface appeared noticeably rougher, with fine, laminar-type deposits. These features are likely associated with the formation of iron–ellagitannin complexes. Indigo-dyed silk, on the other hand, exhibited clustered particulate deposits, with aggregates in the range of 200–400 nm. This observation aligns with earlier reports of indigotin particle deposition (Prabhu and Bhute, 2012).

Importantly, no visible fibre damage or distortion of the cross-sectional structure was observed in any of the mordanted samples at the concentrations used. This suggests that the dyeing process, under the given conditions, does not adversely affect the structural integrity of the silk fibres.

V. DISCUSSION

The findings of this study show that natural dye–mordant systems on mulberry silk are capable of achieving colour fastness levels that are suitable for commercial use, especially in terms of wash and rub fastness, provided that appropriate mordanting conditions are followed. The overall performance trend observed among the dyes—indigo ≥ pomegranate rind > henna > turmeric—can be understood in terms of differences in their chemical structure, molecular weight, and the nature of their interaction with the silk fibre.

The effectiveness of alum as a mordant for turmeric and henna appears to be closely linked to the stability of the metal–dye complexes formed. The aluminium–curcumin complex ($\log K \approx 12.4$) and aluminium lawsone complex ($\log K \approx 9.8$) exhibit greater stability compared to the corresponding ferrous or cupric complexes for these dyes (Vankar et al., 2008). In contrast, the strong performance of ferrous sulphate in the case of pomegranate rind can be explained by the high stability of ferrous–ellagitannin complexes ($\log K \approx 15.2$ for Fe^{2+}–galloyl systems).

From a sustainability perspective, turmeric continues to present a limitation due to its poor light fastness (rating 2), despite its otherwise favourable dyeing characteristics. Future work could focus on improving its photostability, for example, by incorporating UV-absorbing nano-mordants such as zinc oxide or titanium dioxide, or by encapsulating curcumin within cyclodextrin matrices. These approaches may enhance light stability without negatively affecting dye uptake (Rehman et al., 2018). Additionally, the use of myrobalan (Terminalia chebula) as a bio-mordant pre-treatment owing to its high chebulinic acid content—may further improve both K/S values and light fastness, particularly for tannin-based dye systems.

It should be noted that the present study focused solely on pre-mordanting. Including simultaneous and post-mordanting methods in future investigations would provide a more comprehensive understanding of mordant–dye interaction kinetics. This is especially relevant for the pomegranate rind–$FeSO_4$ system, where the high tannin content may lead to competing interactions between mordant uptake and dye complex formation.

From the perspective of reviving traditional Indian handicrafts, these results highlight the strong potential of pomegranate rind and indigo as key natural dyes for Banarasi silk production in Varanasi, particularly for applications targeting eco-label certifications such as GOTS and Oeko-Tex. Their combination of high dye uptake, acceptable fastness properties, and relatively low environmental impact of mordants like ferrous sulphate and alum makes them well-suited for sustainable textile production. For practical implementation at the artisan level, simplified and standardised dyeing procedures based on the optimal conditions identified in this study would be especially beneficial.

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